



## Full length article

## Life-cycle environmental impacts of barley straw valorisation

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## ABSTRACT

Most food manufacturers in industrialised countries produce significant amounts of food wastes during their manufacturing activities. Due to the serious environmental consequences of managing these materials, environmental impact analyses have become popular to identify more sustainable practices for food waste management. Life-Cycle Assessment (LCA) is a useful methodology to assess such environmental impacts. This paper presents the main results obtained using the LCA methodology to analyse the potential environmental impacts of waste management for a brewery in the UK. Initially, the main waste types are identified for this industry: barley straw, malt waste and spent grain, and then barley straw is selected to study its environmental impact in detail. An alternative, more sustainable way to manage barley straw by extracting its wax with supercritical CO<sub>2</sub> is discussed. SimaPro software is used to both quantify potential environmental impacts and evaluate the overall environmental performance of this valorisation opportunity, and to compare its modelled environmental impacts to the current impacts of managing barley straw. Results show that valorising barley straw by this method generates a high environmental impact due to the energy requirements of the processes involved, principally for human toxicity (cancer effects), human toxicity (non-cancer effects) and freshwater ecotoxicity impact categories. Using more energy-efficient processes or an alternative energy source would reduce this environmental impact. The analysis used in this paper allows an objective comparison between different scenarios with the final aim of supporting the use of sustainable solutions for waste management in the food industry.

## 1. Introduction

Beer is the most consumed alcoholic drink worldwide (Colen and Swinnen, 2016). Breweries generate large quantities of waste materials per litre of beer produced, ranging from various types of solid wastes to liquid waste (WRAP, n.d.). Significant amounts of waste materials are also generated in other stages of the beer supply chain, such as at the agricultural stage (Garcia-Garcia et al., 2019), and their management severely impacts on the environment. Current best environmental management practices (BEMPs) in the beer sector look into minimising the environmental impacts of managing these materials generated (Dri et al., 2018). Life-cycle assessment (LCA) is a widely used methodology to assess environmental impacts associated with all life-cycle stages of a product or material. LCA is useful to identify opportunities for pollution prevention and for improving the efficiency of industrial practices (Rebitzer et al., 2004), and as such, its use is increasing not only in the research field but also in the industrial sector.

LCA is also useful to model waste management systems (Winkler and Bilitewski, 2007), and there are many examples of such studies (Laurent et al., 2014). Allesch and Brunner (2014) reviewed 151 articles published until 2014 that investigated decision support for waste

management and concluded that 41% of the studies were based on LCA. Around 50–60% of the articles published in the period 2000–2015 that used LCA to assess solid waste management were dedicated to municipal solid waste (MSW) management (Komilis and Ferrer, 2017).

There are a number of examples of LCA studies used to specifically assess the management of food waste (Bernstad Saraiva Schott et al., 2016). For instance, Lee et al. (2007) analysed environmental ramifications of the manufacturing of feed, composting, incineration and landfilling of separate collection of food waste and MSW in Seoul, and aggregated environmental impacts into global warming, human toxicity, acidification, eutrophication and ecotoxicity. Kim and Kim (2010) assessed dry and wet feeding, composting and landfilling of household food waste, but considered only global warming and resource recovery as environmental impacts. Brancoli et al. (2017) analysed the environmental impact of food waste in retail considering different food waste treatment scenarios and also food waste fractions, i.e. types of food waste. Salemddeb et al. (2018) quantified the environmental impact of anaerobic digestion, composting and incineration of food waste by using a hybrid input-output based LCA. Khoo et al. (2010) assessed environmental impacts of food waste management in Singapore for the same technologies, i.e. anaerobic digestion, composting

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and incineration, although left some considerations out of the scope of the LCA, such as transportation. [Lundie and Peters \(2005\)](#) compared the environmental performance of home composting, centralised composting and landfill of household food waste and concluded that it is necessary to use LCA in combination with other tools that address technical, social and microbiological risk implications to achieve an integrated assessment of the food waste problem.

Due to its increasing use but also complexity, the LCA methodology has been standardised by the International Organization for Standardization, which divides LCA into four main phases: goal and scope, life-cycle inventory analysis (LCI), life-cycle impact assessment (LCIA) and life-cycle interpretation. Currently, their following standards apply: ISO 14040:2006 and ISO 14044:2006. ISO 14040:2006 describes the principles and framework for LCA, including the definition of the four main phases of LCA, provides support for reporting, and describes limitations of LCA, the relationship between the LCA phases and conditions for use of value choices and optional elements ([ISO, 2006a](#)). ISO 14044:2006 specifies requirements and provides guidelines for the phases and areas described in ISO 14040:2006 ([ISO, 2006b](#)). Furthermore, the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC) has published a useful International Reference Life Cycle Data System (ILCD) Handbook that consist of a set of documents in line with ISO standards. The umbrella report for the guidance documents can be found in the JRC Reference Report by [Wolf et al. \(2012\)](#).

This paper applies the LCA methodology to study the environmental impact of managing one of the major waste streams in the supply chain of Molson Coors, a large brewery located in the UK. The waste stream of most interest for the brewery is identified, and then two scenarios of managing this feedstock are explored and compared: current management practices and a valorisation opportunity. This paper, therefore, quantifies the potential environmental impact associated with the implementation of an alternative valorisation process to manage such waste from the beer supply chain.

## 2. Identification of the feedstock and technology for valorisation

Molson Coors Brewing Co. (UK), Ltd. (hereinafter, “Molson Coors”), a subsidiary of the multinational Molson Coors Brewing Company, is one of the largest brewing companies in the UK. The authors held a number of meetings with Molson Coors’ company staff from its site in Burton upon Trent in Staffordshire, resulting in a precise definition of the industrial problem to be tackled and the proposition of a potential solution to valorise a waste stream generated in their supply chain. The following sections explain how this waste is currently managed in Molson Coors’ supply chain and the alternative solution to valorise this material, assess the environmental performance of this waste valorisation opportunity and discuss its potential benefits and drawbacks in comparison with current waste management practices.

Initial interviews with Molson Coors’ staff allowed the identification of the following wastes, common for most breweries and their upstream supply chains: barley straw, malt waste, spent grain, trub, spent yeast, conditioning bottom, filter waste and beer waste. Of these wastes, barley straw and spent grain dominate in terms of volume, with ~80% of the total waste from the farm to the end of Molson Coors’ production line. Molson Coors identified barley straw as the feedstock with most interest for them, thus it was decided to focus this study on the analysis of barley straw management. Currently, around 75,000 tonnes of barley straw per year could be allocated to Molson Coors’ manufacturing activities in Burton upon Trent. This accounts for about 75% of the total beer produced in the UK yearly by Molson Coors. More details about waste types and quantities from Molson Coors can be found in a study by [Garcia-Garcia et al. \(2019\)](#).

Barley is not only widely produced in the UK, but also worldwide due to its high adaptability to different climate areas. Globally, more than 141 million tonnes of barley were produced in 2016, with the top

producers being Russia, Germany, France, Ukraine, Australia and Canada ([FAOSTAT, 2017](#)). However, harvesting barley also generates a significant amount of waste material. Barley straw is the inedible material of the barley plant after the edible grain is removed during harvesting. It is composed mostly of plant straw, which is commonly used for animal feeding and bedding with a current economic value of the order of £50/t in the UK ([Garcia-Garcia et al., 2019](#)). This straw can make up between a third and half of the dry weight of the barley plant ([Sun, 2010; González-García et al., 2018; Garcia-Garcia et al., 2019](#)).

Barley straw can also be used in a range of industrial applications, e.g. production of bio-based building materials ([Laborel-Préneron et al., 2018](#)), second-generation bioethanol ([Vargas et al., 2015; González-García et al., 2018](#)) and production of xylooligosaccharides ([González-García et al., 2018](#)). Particularly, there are opportunities to extract valuable compounds from barley straw, such as cellulose nanocrystals ([Fortunati et al., 2016](#)) and xylitol ([de J.C. Moraes et al., 2018](#)). Although wax makes up a small proportion of the mass content of the barley straw, this material is very valuable due to its properties, such as its performance at different temperatures, and scuff, chemical and electrical resistance, and consequently its various applications, including candle manufacturing, packaging, use in plastic and rubber, and use in cosmetic and toiletries ([Grand View Research, 2017](#)). The global market for wax was valued at \$9322 million in 2016, and it is anticipated to increase to \$11,780 million by 2023 ([Research and Markets, 2018](#)).

Different ways to extract wax from cereal crop wastes have been successfully studied in the past ([Hums et al., 2018; Pham et al., 2018](#)). The use of supercritical carbon dioxide (sCO<sub>2</sub>) extraction to achieve such extraction is of particular interest, due to the low environmental impact of the process, reduced use of solvents and elimination of emissions of volatile organic compounds ([Attard et al., 2018](#)). Taking these aspects into consideration, the valorisation of barley straw by extracting its wax content by sCO<sub>2</sub> extraction is studied in this paper from an environmental point of view. The following sections explain the four phases of LCA applied to this case study.

## 3. Goal and scope definition

The objective of the LCA study presented in this paper is to assess the potential environmental footprint of the processes involved in valorising barley straw with sCO<sub>2</sub> technology, and then to compare it with the environmental impact of the current barley straw treatment. The system under analysis includes all the processes needed to undertake the valorisation, and all emissions and resource depletion associated with the materials and processes used in the valorisation, e.g. electricity and water. Similarly, the emissions and resource depletion associated with the materials and processes used for the current barley straw treatment are considered in the comparison analysis. The treatment of residues and other output streams is within the scope of the analysis. However, no environmental impact has been allocated to the main raw material in the process, i.e. barley straw, following a zero-burden approach along the lines of other waste management studies, e.g. [Thyberg and Tonjes \(2017\)](#) and [Liu et al. \(2017\)](#). Although infrastructure and capital goods often contribute significantly to the overall environmental impact of waste management systems ([Brogaard and Christensen, 2016](#)), these considerations have been left out of the scope of this study due to a lack of data. As a consequence, and taking into account that the model presented in this paper is mostly based on empirical data, it is assumed infrastructure and capital goods to undertake the valorisation are already in place, and only the environmental impacts associated with running the valorisation process and consuming the resources needed are within the scope of this study.

The valorisation analysed in this paper is a small-scale intervention, with negligible effects in existing supply chains of the products substituted due to the small quantity of the outputs produced. Consequently, average data was used to model the background system,

prioritising processes and materials from firstly the UK and secondly Europe. Therefore, an attributional LCA has been used.

The specific process valorisation route to produce wax from barley straw analysed in this paper is based on work undertaken by Sin (2012), who successfully achieved the extraction of wax from barley straw using sCO<sub>2</sub> at a pilot-plant scale. From the several scale sizes and extraction processes described by the aforementioned author, the largest scale trialled that gave positive results was selected. This allowed the treatment of 90 kg of air-dried barley straw to obtain 1.35 kg of pure wax at a pilot-plant scale. Therefore, the functional unit is defined as 1.35 kg of pure wax obtained in one valorisation batch.

The wax obtained from the valorisation of barley straw following this process would be apt for human consumption, and as such, it would replace carnauba wax in the market due to its similar properties and potential applications. Carnauba wax is produced from the leaves of the palm *Copernicia prunifera*, grown in Northeast Brazil (Steinle, 1936). Around 10–16 kt of carnauba wax are produced every year, of which Brazil exports to Europe 2 kt and the US 3–4 kt (Krendlinger et al., 2015). Not only has an attributional approach been used to evaluate the environmental footprint of this process, but also the small amount of wax produced in this method would not have any effect in the existing supply chains of carnauba wax, and therefore a reduction in the supply of carnauba wax by existing methods, and its environmental impact, has not been considered in this study.

Similarly, the straw from the second pelletisation could be used for animal feeding and therefore reduce the need to produce the same amount of animal feed. However, the valorisation process proposed uses barley straw as raw material, which is already used for animal feeding. Since both quantities are virtually the same, as shown in the process flow diagram in Fig. 1 (90 kg of barley straw vs 90.82 kg of pelletised straw), it can be assumed that valorising barley straw by this method would not reduce nor increase the amount of material available for animal feeding. The small difference in the composition of the pelletised straw, with a lower wax concentration but higher moisture, does not make any difference in its final application as animal feed.

#### 4. Inventory analysis

In order to collect relevant environmental data for the inventory phase of LCA, firstly a process flow diagram was prepared to show the main materials used and generated in the process (including emissions), as well as the energy consumption at each stage of the process. This diagram, that can be seen in Fig. 1, was developed based on work from Sin (2012), although this source only specified part of the data required in the LCA model.

The energy consumption for each process in Fig. 1, i.e. kWh of electricity used, was not specified by Sin (2012), and therefore had to be calculated as explained below. The specific equipment utilised for each process, its capacity and the material to be treated (input) according to the mass balances undertaken is listed in Table 1. The capacity of the CLM 935 L G, La Meccanica was taken from the company website (La Meccanica, n.d.; La Meccanica, n.d.), that states that 4500–6000 kg/h can be treated with the 315–355 kW motor power of the CLM 935 L G model. However, the capacity of the Swiss Combi 44 K was unknown and an iterative process was used to estimate it. The capacities of 17 similar electric pellet machines (ABC Machinery, n.d.; ABC Machinery, n.d.) were compared against their power based on different models (ZLSP-D, ZLSP-R and BPM) and sizes. A least-squares linear regression was used, resulting in the data being close to a fitted regression line, with a  $R^2 = 0.9386$ . Using the formula for the linear trendline of such relation between both variables (capacity = 19.052\*power – 101.81) the capacity of a 160-kW electric pellet machine was extrapolated, obtaining the 2947 kg/h as shown in the table. Although a similar approach was followed by Caduff et al. (2011), who concluded that mass vs power relationships of different orders of magnitude in boilers, engines and generators did not scale

isometrically, the extrapolation undertaken here is of the same order of magnitude to that of the empirical values: the highest power from ABC Machinery n.d. and ABC Machinery n.d. is 110 kW, and the extrapolation was undertaken to the value of 160 kW.

For both pelletisation processes, 3.5% of the barley straw mass was added as water to lubricate the straw to aid the pelletisation process. During cooling and drying, it has been estimated that the same amount of water added was removed, simply by leaving the pellets to cool down and dry.

The conditions for the sCO<sub>2</sub> extraction and subsequent separation are defined in Appendix (Table A1). The CO<sub>2</sub> was added to the extractor in a 55:1 proportion to pre-treated straw, and then it was recovered during the separation process and recirculated for the next batch. It has been assumed there is a 1% loss of CO<sub>2</sub> in the process, in the form of an air emission, and therefore 1% of the CO<sub>2</sub> used in the process as a solvent is newly acquired liquid CO<sub>2</sub>. The yields of crude wax and pure wax obtained in both processes were 2.5% and 1.5% of pre-treated straw, respectively.

The energy use allocated to the extraction process is for compressing and heating the liquid CO<sub>2</sub> to the conditions established in Table A1 and run the extraction and separation process, which includes pumping and refrigerating. The energy use, as well as other resource use and emissions to produce liquid CO<sub>2</sub>, is allocated to the liquid CO<sub>2</sub> material and not to the extraction process, as explained by Pellerin (2003). It has been assumed that this material is acquired from an average liquid CO<sub>2</sub> European market, and therefore avoiding double counting in both the material and process. Additionally, although the extractor and separator run simultaneously as a single unit, the resource use has been exclusively allocated to the extraction process, whereas the emissions have been allocated to the separation process, to represent as accurately as possible where the resources are used and the emissions created.

Once the capacity of the equipment is defined, the time needed to treat the amount of material for each process can be easily calculated, and then, multiplying by their power, the energy consumption of each piece of equipment can be obtained.

The energy used to run the extraction process in Evonik Industries' CIT plant in Trostberg (Germany) could not be found by the authors, and based on this lack of data three alternative methodologies have been used to estimate this figure. The first energy estimation is based on an average sCO<sub>2</sub> extraction for plant materials of 0.8 kW h/kg (Pellerin, 2003). The second estimation is from empirical data from a similar sCO<sub>2</sub> extraction system (SepareCo, SCFN I-580DWY/PLC (SepareCo, n.d.)), with an installed power of 110 kW and CO<sub>2</sub> flow of 2500 kg/h, which requires 2 h to provide the 4900 kg CO<sub>2</sub> needed in the process modelled. The third estimation is based on the methodology used by Attard et al. (2015) to calculate the electric power costs of a CO<sub>2</sub> pump, heater and refrigeration system to extract wax from maize stover, a similar process to that modelled in this paper. In this third method, the specific enthalpy is calculated from the extraction pressure and temperature, and next the variation of specific enthalpy is multiplied by the extraction time and CO<sub>2</sub> mass flow rate to obtain the total energy used by the pump (427 kW h). The energy for heating is calculated from the specific heat formula, for which the following values are needed: the CO<sub>2</sub> mass flow, the specific heat capacity of CO<sub>2</sub>, the temperature increase to achieve extraction conditions, and an assumed 50% efficiency, which gives 158 kW h. The energy for the refrigeration is also calculated from the specific heat formula, assuming water is cooled from 20 °C to 4 °C, multiplying by the coefficient of performance (COP) of water at 4 °C (0.15) and dividing by COP of water at 20 °C (0.08), which gives 34.5 kW h. Since these three estimations give values within the same order of magnitude, the average has been used as a core value in the model, whereas the highest and lowest values have been used for sensitivity analysis as explained in Section 6.

Based on the data, calculations and estimations explained above, an inventory table has been created to show the use of resources and emissions created during the valorisation, for each of the processes

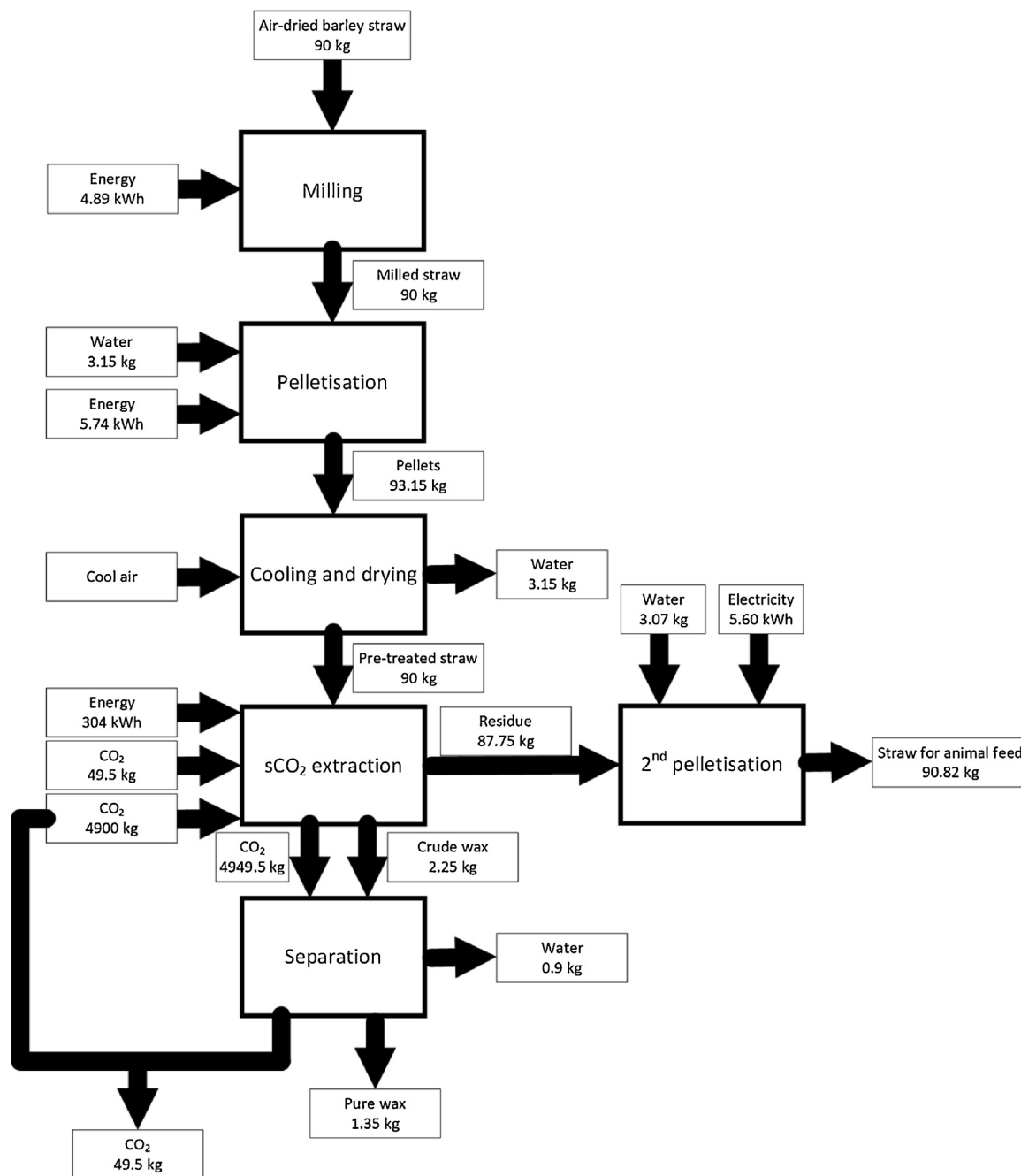


Fig. 1. Process flow diagram to obtain wax from barley straw. Partially based on data from Sin (2012).

involved (Table 2).

Since two products are produced in the process modelled, i.e. wax and straw for animal feeding, there is a multifunctional problem in the model that needs addressing. The decision tree from Davis et al. (2017) (Fig. 3, page 33) has been used to determine the type of study and the

approach to solve the multifunctionality. The initial aim of the LCA study presented in this paper, as explained earlier, is to provide an environmental footprint of the valorisation process, and since the amount of wax produced is small compared to the global offer and the quantity of treated barley straw that can be used for animal feeding is

Table 1  
Equipment used to extract wax from barley straw and energy consumption.

Process	Equipment used	Capacity, kg/h	Input, kg	Power, kW	Time, min	Energy use, kWh
Milling	Swiss Combi 44 K	2947	90	160	1.83	4.887
Pelletisation	CLM 935 L G, La Meccanica 935	5250	90	335	1.03	5.743
Cooling and drying	Allocated to the pelletisation process, no energy use					
sCO <sub>2</sub> extraction & separation	200 L extractors in Evonik Industries' CIT plant in Trostberg, Germany	Unknown	90	304	60	304.1
2nd pelletisation	CLM 935 L G, La Meccanica 935	5250	87.75	335	1.00	5.599

**Table 2**

Inventory table showing the main inputs (resource consumption) and outputs (emissions) of the processes involved in the valorisation of barley straw. Air-dried barley straw (raw material), intermediate products and final products (main product and by-product) are not included in the table.

Process	Inventory category	Consumption/emission	Value	Unit	Reference
Milling	Electricity	Consumption	4.89	kWh	Calculations from data from ABC Machinery (n.d.) and ABC Machinery (n.d.)
Pelletisation	Water	Consumption	3.15	kg	Sin (2012)
	Electricity	Consumption	5.74	kWh	Calculations from data from La Meccanica (n.d.) and La Meccanica (n.d.)
Cooling and drying	Water vapour	Emission	3.15	kg	Assumption from data from Sin (2012)
sCO <sub>2</sub> extraction	Electricity	Consumption	304	kWh	Calculations from data from Pellerin (2003); SepareCo (n.d.) and Attard et al. (2015)
	Liquid CO <sub>2</sub>	Consumption	49.5	kg	Assumption from data from Sin (2012)
2 <sup>nd</sup> pelletisation	Water	Consumption	3.07	kg	Sin (2012)
	Electricity	Consumption	5.60	kWh	Calculations from data from La Meccanica (n.d.); La Meccanica (n.d.)
Separation	Water vapour	Emission	0.9	kg	Sin (2012)
	Gas CO <sub>2</sub>	Emission	49.5	kg	Assumption from data from Sin (2012)

virtually the same as in the status-quo (current) scenario, allocation has been used to solve the multifunctional problem following the attributional framework. Mass allocation was used to allocate environmental impacts to products produced by the same process (i.e. multioutput processes) as in previous LCA studies of food waste valorisation (e.g. Brunklaus et al. (2018)) and recommended by AgroCycle (Chen et al., 2016). Consequently, 2.5% of the environmental impact has been allocated to pre-treated straw to be used for wax production, and 97.5% to pre-treated straw for animal feeding. It is assumed that milling, pelletisation, cooling and drying, and the 2nd pelletisation would also be needed to produce straw for animal feeding in the status-quo scenario and thus the aforementioned mass allocation was used. In contrast, the sCO<sub>2</sub> extraction and separation process is carried out exclusively to extract the wax, and consequently the environmental impact of these processes has been allocated exclusively to wax. An alternative analysis in which economic allocation was used instead of mass allocation is also discussed in the next section.

## 5. Impact assessment

SimaPro 8.5.2 (PRé Sustainability) was used to undertake the phase 3 of LCA, i.e. life-cycle impact assessment (LCIA). “Allocation at the point of substitution” processes, from ecoinvent 3.4 database, were used to model the background system following an attributional approach. The International Reference Life Cycle Data System ILCD 2011 Midpoint + V.1.10 impact assessment method, including long-term emissions and excluding infrastructure, was used in this study, as recommended by the European Commission JRC - IES (2011), unless stated otherwise.

Fig. 2 shows the characterised LCA results for the environmental impact analysis of the valorisation process, showing the contribution to the overall environmental impact from both products generated in the valorisation, i.e. wax and straw for animal feeding. Wax production generates a notably higher environmental impact than production of straw for animal feed, with 95–97% of the contribution to the total environmental impact for the sixteen environmental impact categories analysed with this LCIA method. Similar conclusions were obtained by using the ReCiPe 2016 Midpoint/Endpoint (H) V1.02 and IMPACT 2002 + V2.14 methods, which proves the reliability of the results obtained regardless of the LCIA method chosen. Due to the significant difference in market price of both products, i.e. pure wax and straw for animal feed, if economic allocation were to be used instead of mass allocation, the characterised results in Fig. 2 would show an even proportionally higher environmental impact allocated to pure wax, making the environmental impact of straw for animal feed negligible.

A contribution analysis has been undertaken to elucidate the reason behind this high environmental impact attributed to production of pure wax. The sCO<sub>2</sub> extraction process, that produces the crude wax, contributes the most to the overall environmental impact. This is because of the high energy use of this process. Crude wax contributes between 76% and 96% of the environmental impact for each impact category, with the lowest contribution for climate change and the highest for water resource depletion (see hotspot analysis in Fig. 3). The separation process, in which pure wax is obtained, only shows a significant contribution to the potential environmental impact for the climate change impact category, causing 49.5 kg CO<sub>2</sub> equivalent (15.3% of the total impact for climate change). Aggregating all the results, 91% of the environmental impact of the entire valorisation process modelled

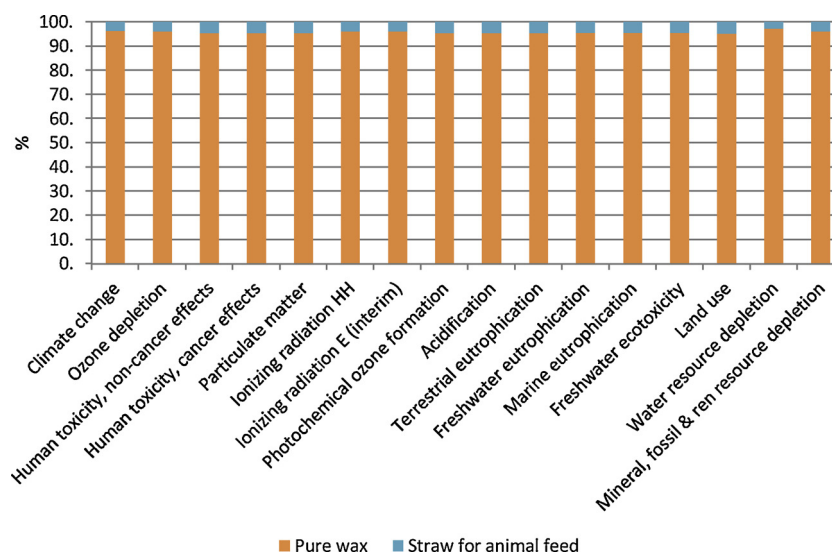


Fig. 2. Characterised results for the production of wax from barley straw and straw for animal feed as by-product.

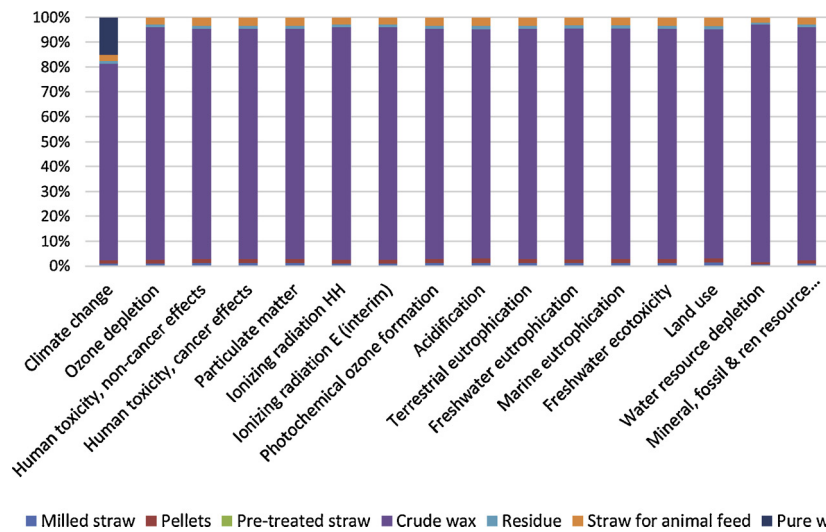


Fig. 3. Characterised results for the valorisation of barley straw showing the contribution of each material.

corresponds to the generation and distribution of electricity used to generate the energy needed in all process stages, and 86% specifically corresponds just to the energy used in the sCO<sub>2</sub> extraction process. This should be the first process to be optimised from an energy-efficiency point of view to reduce the overall environmental impact of the entire valorisation process.

Although only classification and characterisation are mandatory steps in LCIA according to ISO (2006a), additional optional steps such as normalization, grouping, weighting and single scoring are sometimes used in LCA studies (Nikkhah et al., 2019; De Luca et al., 2017). These additional steps are more subjective than classification and characterisation, but they provide valuable information, mostly for non-LCA experts, about the magnitude of the environmental impacts, and also make it possible to easily compare different scenarios (Hauschild and Huijbregts, 2015). Consequently, LCIA results obtained above have been normalised to provide additional insights about the environmental impact categories that contribute the most to the overall environmental impact. A weighting step has not been used since ISO (2006a) specifically advises against this. Fig. 4 shows normalised results with the ILCD 2011 Midpoint + V1.10 EC-JRC Global, equal weighting method. The impact category that contributes the most to the overall environmental impact is human toxicity (cancer effects), with around half of the total normalised environmental impact of the valorisation process, followed

by human toxicity (non-cancer effects) and freshwater ecotoxicity. The environmental impact results for these categories are 4.21E-5 CTUh, 9.59E-6 CTUh and 828 CTUe respectively. These results can be explained by the high toxicity effects attributed to the medium-voltage UK electricity grid from the ecoinvent database, which uses data from the International Energy Agency and the Organisation for Economic Co-operation and Development. In Section 6, an alternative scenario with a different electricity mix is analysed to show how the results depend on the environmental ramifications of the generation and distribution of electricity. The single score calculated with the ILCD 2011 Midpoint + V1.10 EC-JRC Global, equal weighting method, shows a total environmental impact of the entire valorisation process, combining results from both products, of 99.4 mPt. By using the IMPACT 2002 + V2.14 method, the total single score is slightly lower, 75.2 mPt. The impact categories that contribute to this environmental impact are, in decreasing order, the aforementioned human toxicity (cancer effects), human toxicity (non-cancer effects) and freshwater ecotoxicity, followed by ionizing radiation and climate change. The remaining impact categories contribute with negligible values to the total environmental impact.

A scenario analysis has been used to analyse key consequential aspects in order to explain more precisely what the environmental consequences of implementing the valorisation process would be. Results

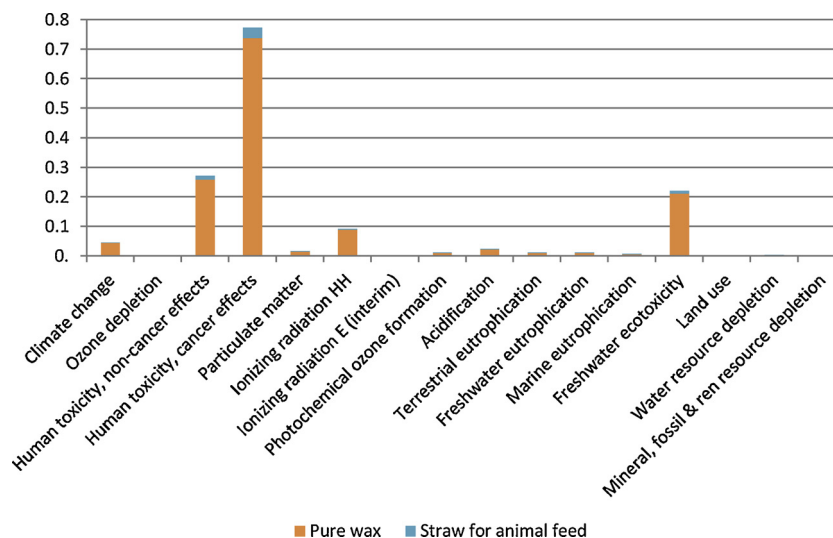


Fig. 4. Normalised results for the production of 1.35 kg of wax from barley straw with straw for animal feed as a by-product.

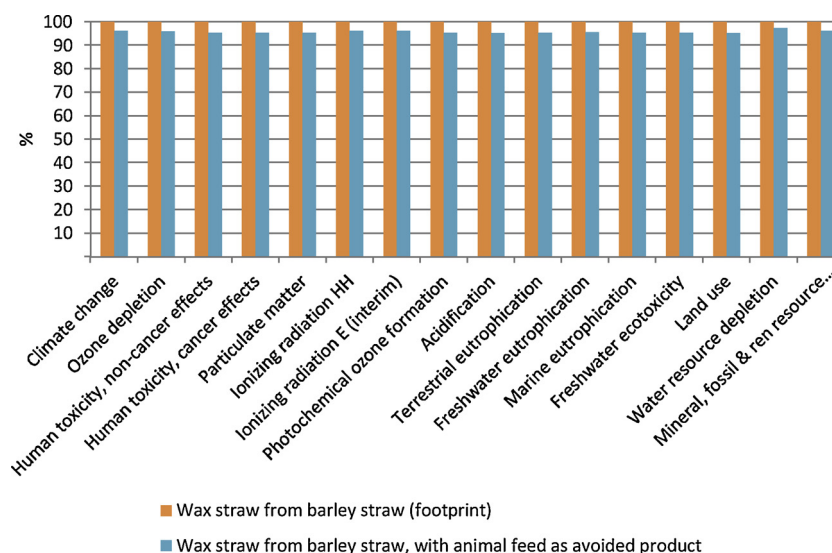


Fig. 5. Comparison between characterised results for the production of wax from barley straw with straw for animal feed as a by-product (footprint, in orange) and without straw for animal feed as a by-product (discounting avoided impacts, in blue).

shown so far in this section are representative of the environmental footprint of the valorisation process; nevertheless, the status-quo scenario also creates an environmental impact, which would be substituted by the environmental footprint analysed so far. In the status-quo scenario, it was initially assumed that barley straw must be treated in the same way as the by-product straw from the valorisation process is treated: milling, two pelletisation processes, and cooling and drying. Since the amount of straw obtained as a by-product is virtually the same as the quantity used as raw material, the environmental impact contribution attributed to straw for animal feed can be discounted from the total environmental footprint, showing what the real additional environmental impact needed to extract wax from barley straw would be. The results of such analysis, in Fig. 5, shows that discounting the impact of the avoided product, i.e. straw for animal feed, the total environmental impact is reduced by only 4–5% in all impact categories, demonstrating that a majority of the environmental impact is allocated to wax. Furthermore, the environmental impact attributed to using barley straw as animal feed (without wax extraction) is a worst-case scenario, since it is unlikely all the processes considered would be needed to treat barley straw for this purpose. If fewer processes are considered in the status quo, the reduction of the environmental impact would be even smaller, with no reduction if barley straw is directly given to animals as feed without any treatment. Therefore, it can be concluded that the environmental impact of the valorisation option studied in this paper is significantly higher than that of the current barley straw management.

## 6. Interpretation

Results presented in Section 5 show that electricity generation and distribution accounts for the majority of the environmental impact of the valorisation process. This is because ecoinvent 3.4 attributes a high proportion of the UK electricity mix to coal, which generates a high environmental impact, particularly due to emissions of toxic substances. Because of this, an alternative electricity mix has been considered to assess the sensitivity of the model to this factor, as in previous studies (Goulart Coelho and Lange, 2018). Photovoltaic (PV) electricity was selected for this comparison analysis because of the current UK government drive to expand solar farm assets in the UK (Palmer et al., 2019) and the constant increase of installed capacity of PV energy in recent years in the UK, second of all renewable capacity only behind onshore wind (Department for Business, Energy and Industrial Strategy (UK), 2019). PV installations are easy to install and

maintain compared to other alternatives, thus it would be easier to install PV solar panels near the location where the barley straw valorisation process takes place than, for example, installing wind turbines. The PV electricity used in this alternative scenario is produced in a PV plant with a total capacity of 570 kWp (data from ecoinvent 3.4), which is enough to provide the energy needed to run the valorisation processes simultaneously according to Table 1. The PV plant is an open ground installation that it is assumed to produce low-voltage electricity, with no transformation. According to ecoinvent 3.4, transformation processes in open-ground PV installations only have a low influence on the environmental impact.

Results from this LCA comparison can be seen in Fig. 6, which shows a significant reduction in the environmental impact for all impact categories by using PV electricity. The environmental impact categories that contributed the most to the overall environmental impact in the scenario with the UK electricity mix, i.e. human toxicity (cancer and non-cancer effects) and freshwater ecotoxicity, are reduced by 91–93%, which means that the overall environmental impact of this alternative scenario must be significantly smaller than in the current scenario. The single score of both electricity generation options have been compared to confirm this, and the overall environmental impact is indeed reduced by 91% by using PV electricity. There is significant variability in the reduction of environmental impact for each category, ranging from 97% for land use to 49% for water resource depletion.

In conclusion, the valorisation process is very sensitive to the source of electricity, both for the overall environmental impact and also within each environmental impact category. This type of scenario analysis can be used to estimate environmental impacts of the valorisation process with a projected future electricity mix, e.g. with more renewable energy and a lower fossil-fuel consumption, or for different locations of the valorisation plant, e.g. based in the UK (which has a high environmental impact attributed per kWh of electricity generated) versus based in France (with its lower emissions of greenhouse gas and toxic substances, partially explained by the much-higher contribution of nuclear energy into its electricity mix).

In addition to the contribution and scenario analyses carried out to analyse the sensitivity of the model, for which the main results were shown in this and the previous section, the absolute uncertainty of the model developed has also been assessed in order to evaluate the reliability of the results. Stochastic simulation, specifically the Monte Carlo method, has been used to calculate the value of the model variables, to which certain probabilities were assigned. Lognormal distributions

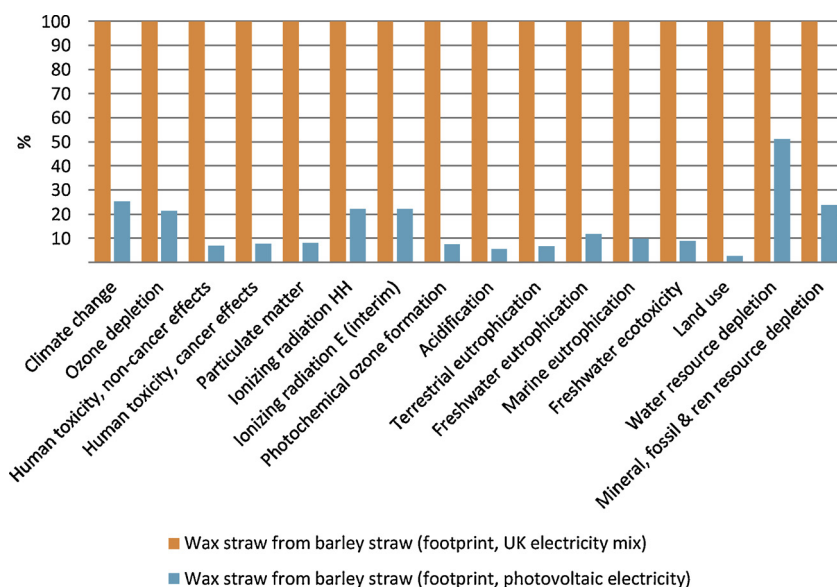


Fig. 6. Comparison between the characterised results of the total environmental impact of the valorisation process using UK electricity mix (orange) and photovoltaic electricity generation (blue).

were used for most variables, as they are the most important distributions in LCA and are used by ecoinvent by default (Goedkoop et al., 2016). Triangular distributions were used to represent the electricity usage of the pelletisers, extractor and separator, and CO<sub>2</sub> emissions to air, as preferred (standard), minimum and maximum values were known. For the pelletisers, the minimum (maximum) value corresponds to the lowest (highest) power in the power range specified by the manufacturer multiplied by the time of the extraction divided (multiplied) by 1.1 (i.e. lognormal distribution with 10% uncertainty). For the extractor and separator, the minimum and maximum values correspond to the lowest and highest values from the three calculation methods used as explained in Section 4. For the CO<sub>2</sub> emissions to air, it has been estimated that the minimum emission is zero (i.e. no CO<sub>2</sub> loss), maximum is 5% and preferred is the 1% value used in Fig. 1. In all cases the preferred value of electricity use corresponds to the mean for each value range. The square geometric standard deviation of the lognormal distributions were assumed to correspond to an uncertainty of 10% for technology (input) parameters and 20% for emission values, based on Bisinella et al. (2016).

The main result from the absolute uncertainty analysis undertaken by the Monte Carlo method with 10,000 runs is shown in Fig. 7. In the model, a total of 646,659 materials and processes were used, of which in terms of uncertainty 73.4% were assigned a lognormal distribution, 26.5% were undefined, 0.0309% were assigned a triangle distribution and 0.0119% a normal distribution. The total environmental impact of the valorisation process, as a single score, is between 0.0223 and 0.335 Pt at a confidence interval of 95%. The large coefficient of variation obtained in this analysis can be explained by the mean value being close to zero (0.108 Pt in the iteration shown in Fig. 7). The environmental impact category that contributes to this most significantly, with the highest coefficient of variation, is water resource depletion, since its mean values at a confidence interval of 95% are around zero with both positive and negative values. In terms of materials and processes, electricity generation and distribution, which contributes the most to the overall environmental impact, has a significantly high coefficient of variation of 90.5% in ecoinvent 3.4. The standard deviation of the single-score environmental impact analysis is 0.159, and the standard error of mean is 0.00159. Generally, standard error of means below 0.01 are acceptable for most models (Goedkoop et al., 2016), and therefore the LCA results presented in this section can be considered reliable and consistent.

As a conclusion from the interpretation of the results obtained from this LCA study, valorising barley straw to extract its wax creates a high environmental impact using sCO<sub>2</sub> and current energy sources in the UK power grid, significantly higher than in a no-valorisation scenario. Nevertheless, barley straw valorisation delivers a new product that can be commercialised, i.e. wax, and therefore an economic analysis could justify implementing such valorisation process. Future work should investigate the environmental impacts of producing the wax that this product could substitute (carnauba wax). If this impact is proven to be higher than the environmental footprint shown in this paper, the implementation of the valorisation process would also be justified from an environmental angle. However, quantifying the environmental impact of carnauba wax production is a very complex task due to lack of data. It is expected that the costs and environmental impact associated with transportation would be significantly reduced in the valorisation scenario, since currently carnauba wax is only produced in Brazil and then distributed worldwide. Localised wax production, in regions where barley is harvested in large amounts, e.g. UK, would significantly reduce such ramifications from transportation, since wax can be considered a commodity that is used in products that are consumed worldwide.

## 7. Conclusions

Barley straw is one of the major waste streams generated in the beer supply chain. Currently, it has a low economic value and is commonly used for animal feeding. In order to better understand the environmental impact of managing this material, the LCA procedure has been applied to a case study with a large Molson Coors' brewery located in the UK. Current treatments and an identified opportunity to valorise barley straw have been assessed by using LCA. Data from successful pilot-plant scale trials of extraction of wax from barley straw using supercritical CO<sub>2</sub> have been used to model the valorisation scenario. LCA results show that valorising barley straw by this method generates a high environmental impact due to the energy requirements of the processes involved, principally the supercritical extraction process. This environmental impact is significantly higher than that of the current barley straw management. The impact categories that more significantly contribute to the environmental impact are, in decreasing order, human toxicity (cancer effects), human toxicity (non-cancer effects) and freshwater ecotoxicity.



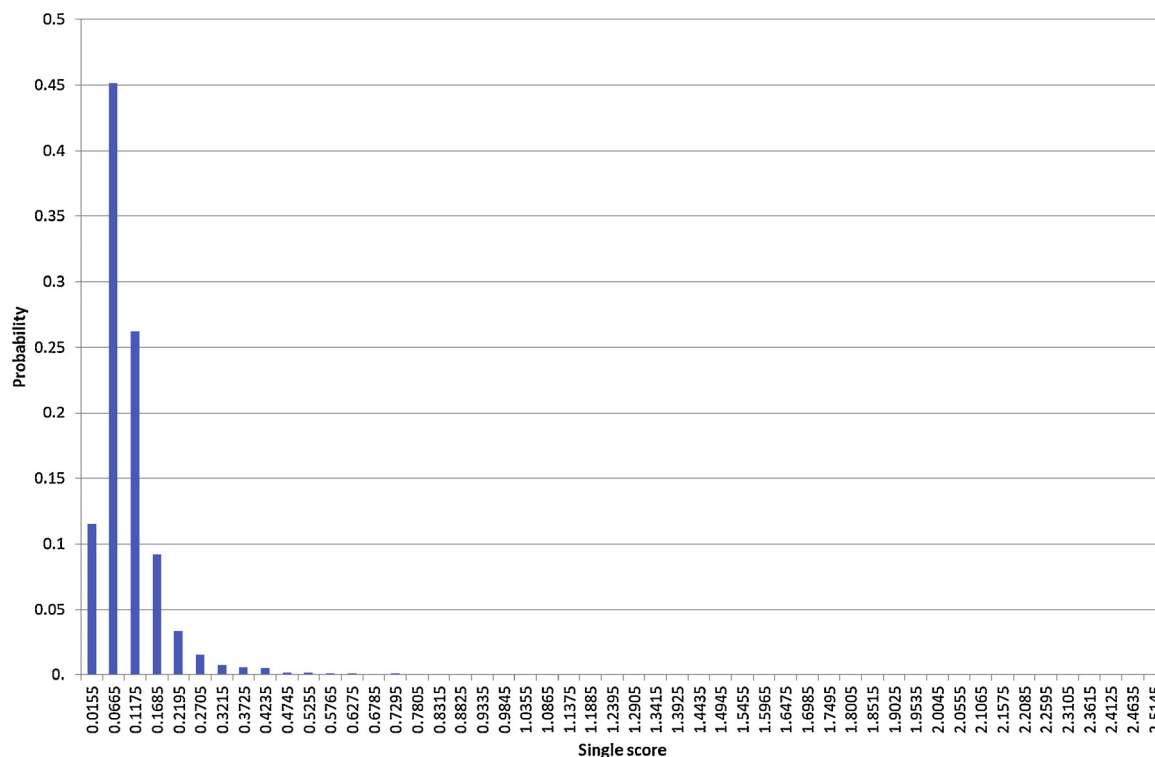


Fig. 7. Uncertainty analysis of the single score of the valorisation process.

Nevertheless, the product obtained from the process, i.e. wax, has a growing global market demand and therefore the valorisation process proposed could attract industrial interest. It is expected that this wax would compete in the market with waxes with similar properties, e.g. carnauba wax. It is also anticipated that if this valorisation process were to be implemented at a large scale, rather than the pilot-plant scale studied in this paper, it would be optimised to reduce production costs, so the wax produced would be competitive in the wax market. Particularly, the valorisation process should be optimised from an energy-efficiency angle, consequently reducing the environmental impact of the valorisation process per kg of wax obtained. Also, using alternative, more sustainable sources of electricity, such as photovoltaic energy, would significantly decrease the environmental impact of such valorisation. It is predicted that the contribution of coal to the current UK electricity mix will be reduced in coming years, whereas the contribution of renewable energy to the mix will increase, causing an inevitable decrease in the environmental impact of the waste valorisation process studied in this paper.

**Appendix A**

This appendix contains the conditions for the extraction and separation of wax from barley straw (Table A1).

**Table A1**  
Conditions for the extraction and separation, based on work by Sin (2012).

	sCO <sub>2</sub> extraction	Separation
Temperature, K	343	343
Pressure, MPa	26	5.5
Time, h	1	1
Volume, L	200	200
sCO <sub>2</sub> used, kg	4950	4950

**Declarations of interest**

None.

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## References

- ABC Machinery, n.d. Flat die wood pellet machine [Online] Available at: (<http://www.bestpelletplant.com/Small-Pellet-Machine.html>) (accessed on 19 November 2018).
- ABC Machinery, n.d. Ring die wood pellet machine [Online] Available at: (<http://www.bestpelletplant.com/Wood-Pellet-Machine.html>) (accessed on 19 November 2018).
- Allesch, A., Brunner, P.H., 2014. Assessment methods for solid waste management: a literature review. *Waste Manag. Res.* 32, 461–473. <https://doi.org/10.1177/0734242X14535653>.
- Attard, T.M., McElroy, C.R., Hunt, A.J., 2015. Economic assessment of supercritical CO<sub>2</sub> extraction of waxes as part of a maize stover biorefinery. *Int. J. Mol. Sci.* 16, 17546–17564. <https://doi.org/10.3390/ijms160817546>.
- Attard, T.M., Bukhanko, N., Eriksson, D., Arshadi, M., Geladi, P., Bergsten, U., Budarin, V.L., Clark, J.H., Hunt, A.J., 2018. Supercritical extraction of waxes and lipids from biomass: a valuable first step towards an integrated biorefinery. *J. Clean. Prod.* 177, 684–698. <https://doi.org/10.1016/J.JCLEPRO.2017.12.155>.
- Bernstad Saraiva Schott, A., Wenzel, H., la Cour Jansen, J., 2016. Identification of decisive factors for greenhouse gas emissions in comparative lifecycle assessments of food waste management – an analytical review. *J. Clean. Prod.* 119, 13–24. <https://doi.org/10.1016/j.jclepro.2016.01.079>.
- Bisinella, V., Conradsen, K., Christensen, T.H., Astrup, T.F., 2016. A global approach for sparse representation of uncertainty in life cycle assessments of waste management systems. *Int. J. Life Cycle Assess.* 21, 378–394. <https://doi.org/10.1007/s11367-015-1014-4>.
- Brancoli, P., Roustia, K., Bolton, K., 2017. Life cycle assessment of supermarket food waste. *Resour. Conserv. Recycl.* 118, 39–46. <https://doi.org/10.1016/j.resconrec.2016.11.024>.
- Brogaard, L.K., Christensen, T.H., 2016. Life cycle assessment of capital goods in waste management systems. *Waste Manag.* 56, 561–574. <https://doi.org/10.1016/j.wasman.2016.07.037>.
- Brunklaus, B., Rex, E., Carlsson, E., Berlin, J., 2018. The future of Swedish food waste: an environmental assessment of existing and prospective valorization techniques. *J. Clean. Prod.* 202, 1–10. <https://doi.org/10.1016/J.JCLEPRO.2018.07.240>.
- Caduff, M., Huijbregts, M.A.J., Althaus, H.-J., Hendriks, A.J., 2011. Power-law relationships for estimating mass, fuel consumption and costs of energy conversion equipments. *Environ. Sci. Technol.* 45, 751–754. <https://doi.org/10.1021/es103095k>.
- Chen, W., Oldfield, T., Holden, N.M., 2016. D6.1 Integrated Sustainability Assessment Framework - Including definition of the details, requirements and guidelines for LCA, LCC and S-LCA Analysis. *AgroCycle*.
- Colen, L., Swinnen, J., 2016. Economic growth, globalisation and beer consumption. *J. Agric. Econ.* 67, 186–207. <https://doi.org/10.1111/1477-9552.12128>.
- Davis, J., De Menna, F., Unger, N., Östergren, K., Loubiere, M., Vittuari, M., 2017. Generic strategy LCA and LCC - Guidance for LCA and LCC focused on prevention, valorisation and treatment of side flows from the food supply chain. REFRESH ISBN 978-91-88349-84-2.
- De Luca, A.I., Iofrida, N., Leskinen, P., Stillitano, T., Falcone, G., Strano, A., Gulisano, G., 2017. Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: insights from a systematic and critical review. *Sci. Total Environ.* 595, 352–370. <https://doi.org/10.1016/j.scitotenv.2017.03.284>.
- de J.C. Moraes, E., Silva, D.D.V., Dussán, K.J., Tesche, L.Z., Silva, D.Ébora Danielle Virgínio, Dussán, Kelly Johana, Tesche, Luana Zanchetta, de Almeida Silva, Joao Batista, Rai, Mahendra, das Graças de Almeida Felipe, Maria, 2018. Xylitol-sweetener production from barley straw: optimization of acid hydrolysis condition with the energy consumption simulation. *Waste Biomass Valorization* 1–13. <https://doi.org/10.1007/s12649-018-0501-9>.
- Department for Business Energy & Industrial Strategy (UK), 2019. National Statistics. Energy Trends: Renewables. Renewable Electricity Capacity and Generation. [Online] Available at: (<https://www.gov.uk/government/statistics/energy-trends-section-6-renewables>) (accessed on 8 March 2019).
- Dri, M., Antonopoulos, I.S., Canfora, P., Gaudillat, P., 2018. Best Environmental Management Practice for the Food and Beverage Manufacturing Sector. Learning From Frontrunners. <https://doi.org/10.2760/2115>.
- European Commission Joint Research Centre - Institute for Environment and Sustainability, 2011. Recommendations for life cycle impact assessment in the European context - based on existing environmental impact assessment models and factors. ILCD Handbook International Reference Life Cycle Data System. <https://doi.org/10.278/33030>.
- FAOSTAT, 2017. Crops/Regions/World List/Production Quantity for Barley. [Online] Available at: <http://www.fao.org/faostat/en/#data/QC> (accessed on 13 December 2018).
- Fortunati, E., Benincasa, P., Balestra, G.M., Luzi, F., Mazzaglia, A., Del Buono, D., Puglia, D., Torre, L., 2016. Revalorization of barley straw and husk as precursors for cellulose nanocrystals extraction and their effect on PVA-CH nanocomposites. *Ind. Crops Prod.* 92, 201–217. <https://doi.org/10.1016/J.INDCROP.2016.07.047>.
- Garcia-Garcia, G., Stone, J., Rahimifard, S., 2019. Opportunities for waste valorisation in the food industry – a case study with four UK food manufacturers. *J. Clean. Prod.* 211, 1339–1356. <https://doi.org/10.1016/J.JCLEPRO.2018.11.269>.
- Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2016. Introduction to LCA With SimaPro.
- González-García, S., Morales, P.C., Gullón, B., 2018. Estimating the environmental impacts of a brewery waste-based biorefinery: bio-ethanol and xylooligosaccharides joint production case study. *Ind. Crops Prod.* 123, 331–340. <https://doi.org/10.1016/J.INDCROP.2018.07.003>.
- Goulart Coelho, L.M., Lange, L.C., 2018. Applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. *Resour. Conserv. Recycl.* 128, 438–450. <https://doi.org/10.1016/J.RESCONREC.2016.09.026>.
- Grand View Research, 2017. Wax Market Size & Share | Global Industry Research Report, 2018–2025. [Online] Available at: (<https://www.grandviewresearch.com/industry-analysis/wax-market>) (accessed on 13 December 2018).
- Hauschild, M.Z., Huijbregts, M.A.J., 2015. Introducing life cycle impact assessment. In: Hauschild, M.Z., Huijbregts, M.A.J. (Eds.), *Life Cycle Impact Assessment*, pp. 1–16. <https://doi.org/10.1007/BF02978760>.
- Hums, M.E., Moreau, R.A., Powell, M.J., Hoyt, J.L., 2018. Extraction of surface wax from whole grain sorghum. *J. Am. Oil Chem. Soc.* 95, 845–852. <https://doi.org/10.1002/aocs.12088>.
- ISO, 2006a. ISO 14040:2006. Environmental Management - Life Cycle Assessment - Principles and Framework. [Online] Available at: (<https://www.iso.org/standard/37456.html>) (accessed on 1 March 2017).
- ISO, 2006b. ISO 14044:2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. [Online] Available at: (<https://www.iso.org/standard/38498.html>) (accessed on 1 March 2017).
- Khoo, H.H., Lim, T.Z., Tan, R.B.H., 2010. Food waste conversion options in Singapore: environmental impacts based on an LCA perspective. *Sci. Total Environ.* 408, 1367–1373. <https://doi.org/10.1016/j.scitotenv.2009.10.072>.
- Kim, M.-H., Kim, J.-W., 2010. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. *Sci. Total Environ.* 408, 3998–4006. <https://doi.org/10.1016/j.scitotenv.2010.04.049>.
- Komilis, D., Ferrer, A.S., 2017. Life cycle assessment in solid waste management: facts and artefacts. *Waste Manag.* 61, 1–2. <https://doi.org/10.1016/j.wasman.2017.03.016>.
- Krendlinger, E., Wolfmeier, U., Schmidt, H., Heinrichs, F., Michalczyk, G., Payer, W., Dietsche, W., Boehlke, K., Hohner, G., Wildgruber, J., 2015. Waxes. *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. [https://doi.org/10.1002/14356007.a28\\_103.pub2](https://doi.org/10.1002/14356007.a28_103.pub2).
- La Meccanica, n.d. Pellet mill [Online] Available at: (<https://www.lameccanica.it/en/wood-biomass/pellet-mill>) (accessed 7 March 2019a).
- La Meccanica, n.d. The CLM935 M-LG pellet mill [Online] Available at: (<https://www.lameccanica.it/en/news/rassegna-stampa-tecnica/clm935-m-lg-pellet-mill>) (accessed 7 March 2019b).
- Laborel-Préneron, A., Magniont, C., Aubert, J.-E., 2018. Characterization of Barley Straw, hemp shiv and corn cob as resources for bioaggregate based building materials. *Waste Biomass Valorization* 9, 1095–1112. <https://doi.org/10.1007/s12649-017-9895-z>.
- Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H., 2014. Review of LCA studies of solid waste management systems - Part I: lessons learned and perspectives. *Waste Manag.* 34, 573–588. <https://doi.org/10.1016/j.wasman.2013.10.045>.
- Lee, S.-H., Choi, K.-I., Osako, M., Dong, J.-I., 2007. Evaluation of environmental burdens caused by changes of food waste management systems in Seoul, Korea. *Sci. Total Environ.* 387, 42–53. <https://doi.org/10.1016/j.scitotenv.2007.06.037>.
- Liu, G., Hao, Y., Dong, L., Yang, Z., Zhang, Y., Ulgiati, S., 2017. An emergy-LCA analysis of municipal solid waste management. *Resour. Conserv. Recycl.* 120, 131–143. <https://doi.org/10.1016/j.resconrec.2016.12.003>.
- Lundie, S., Peters, G.M., 2005. Life cycle assessment of food waste management options. *J. Clean. Prod.* 13, 275–286. <https://doi.org/10.1016/j.jclepro.2004.02.020>.
- Nikkhah, A., Firouzi, S., El Haj Assad, M., Ghnimi, S., 2019. Application of analytic hierarchy process to develop a weighting scheme for life cycle assessment of agricultural production. *Sci. Total Environ.* 665, 538–545. <https://doi.org/10.1016/J.SCITOTENV.2019.02.170>.
- Palmer, D., Gottschalg, R., Betts, T., 2019. The future scope of large-scale solar in the UK: site suitability and target analysis. *Renew. Energy* 133, 1136–1146. <https://doi.org/10.1016/J.RENEVE.2018.08.109>.
- Pellerin, P., 2003. Comparing extraction by traditional solvents with supercritical extraction from an economic and environmental standpoint. *Proceedings of the 6th International Symposium on Supercritical Fluids*.
- Pham, T.-C.-T., Angers, P., Ratti, C., 2018. Extraction of wax-like materials from cereals. *Can. J. Chem. Eng.* 96, 2273–2281. <https://doi.org/10.1002/cjce.23260>.
- Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* 30, 701–720. <https://doi.org/10.1016/j.envint.2003.11.005>.
- Research and Markets, 2018. Wax Market by Type and Application - Global Opportunity Analysis and Industry Forecast. pp. 2017–2023. [Online] Available at: ([https://www.researchandmarkets.com/research/w9t7xb/global\\_wax\\_market?w=4](https://www.researchandmarkets.com/research/w9t7xb/global_wax_market?w=4)) (accessed on 13 December 2018).
- Salemdeeb, R., Mohammad, B.D., Reynolds, C., Al-Tabbaa, A., 2018. An environmental evaluation of food waste downstream management options: a hybrid LCA approach. *Int. J. Recycl. Org. Waste Agric.* 1. <https://doi.org/10.1007/s40093-018-0208-8>.
- SeparCo, n.d. Separco - Dual/triple 580 [Online] Available at: (<http://www.separeco.com/index.php/en/supercritical-fluid-systems/industrial-systems/21-industrial/112-dual-500>) (accessed 5 December 2018).
- Sin, E., 2012. The Extraction and Fractionation of Waxes From Biomass. University of York EthosID uk.bl.ethos.561078.
- Steinle, J.V., 1936. Carnauba wax: an expedition to its source. *Ind. Eng. Chem.* 28, 1004–1008. <https://doi.org/10.1021/ie50321a003>.
- Sun, R., 2010. Cereal Straw As a Resource for Sustainable Biomaterials and Biofuels: Chemistry, Extractives, Lignins, Hemicelluloses and Cellulose, 1st ed. .
- Thyberg, K.L., Tonjes, D.J., 2017. The environmental impacts of alternative food waste treatment technologies in the U.S. *J. Clean. Prod.* 158, 101–108. <https://doi.org/10.1016/j.jclepro.2017.04.169>.
- Vargas, F., Domínguez, E., Vila, C., Rodríguez, A., Garrote, G., 2015. Agricultural residue valorization using a hydrothermal process for second generation bioethanol and

- oligosaccharides production. *Bioresour. Technol.* 191, 263–270. <https://doi.org/10.1016/j.biortech.2015.05.035>.
- Winkler, J., Bilitewski, B., 2007. Comparative evaluation of life cycle assessment models for solid waste management. *Waste Manag.* 27, 1021–1031. <https://doi.org/10.1016/j.wasman.2007.02.023>.
- Wolf, M.-A., Pant, R., Chomkhamri, K., Sala, S., Pennington, D., 2012. *The International Reference Life Cycle Data System (ILCD) Handbook*. European Commission. JRC references reports ISBN: 9789279216404.
- WRAP, n.d. Resource efficiency in the UK brewing sector. [Online] Available at: (<http://www.wrap.org.uk/sites/files/wrap/BeerGuidance%FINAL%010512%AG.pdf>) (accessed on 19 November 2018).